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EFFECTS OF SOIL COMPACTION AND WATER-FILLED PORE SPACE ON SOIL MICROBIAL ACTIVITY AND N LOSSES

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ABSTRACT: Soil compaction is a significant production problem for agriculture because of its negative impact on plant growth, which in many cases has been attributed to changes in soil N transformations. A laboratory experiment was conducted to study the effect of soil compaction and water-filled pore space on soil microbial activity and N losses. A hydraulic soil compaction device was used to evenly compress a Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Kandiudults) soil into 50 mm diameter by 127 mm long cores. A factorial arrangement of three bulk density levels (1.4, 1.6, and 1.8 Mg/m^3) and four water-filled pore space levels (60, 65, 70, 75%) was used. Fertilizer application of 168 kg N/ha was made as 1.0 atom % ^{15}N as NH_4NO_3. Soil cores were incubated at 25°C for 21 d. Microbial activity decreased with both increasing water-filled pore space and soil bulk density as measured by CO_2-C entrapment. Nitrogen loss increased with increasing bulk density from 92.8 to 334.4 g N/m^3 soil at 60% water-filled pore space, for 1.4 and 1.8 Mg/m^3, respectively. These data indicate that N loss and soil microbial activity depends not only on the pore space occupied by water, but also on structure and size of soil pores which are altered by compaction.

INTRODUCTION

The negative effect of soil compaction on crop production is well established (1, 2, 3, 4). The detrimental effect of soil compaction has often been attributed to reduced N uptake (3, 4, 5, 6, 7). While physical impedance of root growth by soil compaction and physical stress on roots has been shown to reduce N uptake (4, 5), alterations of soil N transformation processes, especially mineralization and denitrification, have generally been credited with reduced N uptake (3, 6, 7). For example, Bakken et al. (3) reported a 3-4 fold increase in N loss with compaction via denitrification, resulting in wheat (*Triticum aestivum* L.) yield losses, while Maidl and Fischbeck (7) reported decreases in sugarbeet (*Beta vulgaris* L.) yield due to both reduction in N mineralization and high denitrification with soil compaction.

Alteration of N transformation processes in compacted soils has been attributed to changes in soil moisture level resulting from increased bulk density (reduced soil porosity) (8). Soil moisture level has been shown to directly affect microbial regulated N transformations in soil, including ammonification, nitrification, organic matter decomposition, and denitrification (9, 10, 11 12). Linn and Doran (12) suggested that maximum soil aerobic microbial activity for N transformations occurs at approximately 60% water holding capacity.

Nitrogen losses via denitrification occur only under anaerobic conditions, with a maximum rate of denitrification at soil moisture levels above 70% water holding capacity (12). However, soil structure can also affect denitrification rates (13). Soil aggregates can remain saturated even after pores between aggregates have drained, resulting in conditions conducive to denitrification (14). This indicates that structure and size of soil pores, as well as the total pore space, are important as determinants of denitrification rate.

Changes in microbial activity and denitrification rate in soils as affected by moisture level have been extensively studied. However, few studies have examined the effect of changes in soil physical condition on N transformations. In particular, there is a paucity of information concerning the effect of soil compaction on soil microbial activity and N transformations. Linn and Doran (12) conducted a laboratory study and reported that microbial respiration in a silty clay loam soil was slightly decreased with soil compaction. However, they did not measure soil N losses. Changes in structure and size of pores as well as the amount of pore space filled with water could explain the decrease in microbial activity observed in their study.

The sandy soils of the coastal plain region of the U.S. are highly susceptible to compaction and are generally less structured as compared to heavier textured soils (15). The formation of tillage pans in these soils are common, but surface compaction can also occur, leaving compacted zones corresponding to tire traffic (16). Microbial activity in these zones are likely to be different than that of soil as a whole. While it is not clear whether compaction greatly disturbs structure of these sandy soils, increased compaction is likely to alter the proportion of soil pore sizes. The objective of this study was to examine the effects of soil compaction and water-filled pore space on microbial activity and loss of both fertilizer-derived and soil-derived N in a sandy coastal plain soil.

MATERIALS AND METHODS

A laboratory experiment was conducted to determine the effect of soil compaction and water-filled pore space on soil microbial activity and N loss. Using a hydraulic soil compactor (17), a Norfolk loamy sand soil was compacted into 50 mm diameter by 127 mm long PVC cores to bulk densities within the range found at the field site from which the soil was collected. Norfolk loamy sand was chosen because it is a sandy soil of wide distribution in the coastal plain region of the U.S. Soil (collected from the upper 15 cm of a field site at the E.V. Smith Research Center of the Alabama Agricultural Experiment Station in east-central Alabama, USA) was air dried, sieved to pass 2 mm, and moistened with deionized water to 10.2 % moisture (weight basis) before compaction. The hydraulic compactor utilized two opposing hydraulic cylinders to evenly compress soil samples. A 4-way directional control valve and volumetric flow divider was used to divide flow between hydraulic cylinders, resulting in a uniformly compressed soil core. After compression, cores were trimmed to exactly 127 mm and a sheet of plastic (held in place with a rubber band) was placed on the bottom of each core to hold the soil in place.

The experimental design was a factorial of three bulk density levels (1.4, 1.6, and 1.8 Mg/m^3) and four soil moisture levels (60, 65, 70, and 75% water-filled pore space) with three replications. Soil moisture content was based on water-filled pore space instead of water holding capacity, because water holding capacity of soils is a somewhat ambiguous term that depends on soil type and method of determination (12). The water-filled pore space levels were selected to include an anticipated range covering both aerobic and anaerobic microbial activity. Total pore space was calculated from the equation: $TP = (1 - P_B/P_P)$; where TP = total soil porosity, P_B = soil bulk density, and P_P = soil particle density (assumed to be 2.65 Mg/m^3).

After compaction, deionized water was added to each core in amounts needed to provide the four levels of water-filled pore space. Consistent levels of water-filled pore space were insured by correcting water additions for changes in total soil porosity due to changes in soil bulk density as determined for each core.

Addition of fertilizer N was made to cores at a rate equivalent to 168 kg N/ha. Fertilizer application was made with the final water addition in the form of 1.0 atom % ^{15}N of NH_4NO_3.

Soil cores were placed in 1-L Jars containing 20 mL of water to maintain humidity, and a vial containing 10 mL of 1*M* NaOH to trap respired CO_2 (18). Sealed jars were incubated in the dark at 25°C, for 21 d. Jars were opened and resealed at 7 d intervals to provide adequate O_2. Carbon dioxide in NaOH traps was determined by titrating excess base with 1*M* HCL in the presence of $BaCl_2$ (19). Respired CO_2-C was taken as a measure of aerobic soil microbial activity. After incubation, soil total N concentration was determined using a permanganate-reduced iron modification of the semimicro Kjeldahl method described by Bremner and Mulvaney (20). Distillates from total N analysis were retained for ^{15}N analysis with an automated mass spectrometer (21). Nitrogen content in soil cores was partitioned into soil native N and fertilizer N, and these data, along with initial soil N content and fertilizer N addition, were used to calculate losses of soil native N, fertilizer N and total N.

Analyses of variance and regression analysis were conducted with the SAS package (22). Unless otherwise noted, all statistical test were performed at the $\alpha = 0.05$ level of significance.

RESULTS AND DISCUSSION

Microbial activity as measured by soil respiration was affected by water-filled pore space (Table 1). The highest level of soil respiration was observed in the 60% water-filled pore space treatment (116.7 mg CO_2-C/kg). For water-filled pore space levels greater than 60%, soil respiration was significantly reduced. There was no difference in soil respiration between 65 and 75% water-filled pore space, although the same trend of reduced soil respiration was observed. These findings are consistent with research conducted by Doran et al. (23) who reported maximum soil respiration at 55-61% water-filled pore space and reduced microbial respiration at soil moisture contents above that level.

Bulk density also had a significant effect on soil microbial activity (Table 1). As bulk density increased, soil respiration was reduced within the same level of water-filled pore space. Soil respiration was much lower at a bulk density of 1.8 Mg/m^3 compared to 1.4 Mg/m^3, with a 65% reduction of microbial activity at 60% water-filled pore space. This indicates that soil bulk density affects soil microbial activity in ways other than just alteration of soil moisture levels.

Soil native N losses were significantly increased by both increasing water-filled pore space and increasing soil bulk density (Table 2). Soil bulk density had a much greater effect on native N loss than did water-filled pore space, with an average native N loss increase of approximately 5% from 60 to 75% water-filled pore space, compared to an average soil native N loss increase of 286% from 1.4 to 1.8 Mg/m^3 soil bulk density. The effect of water-filled pore space on soil native N loss was much greater at lower bulk density levels, with soil native N loss from 60 to 75% water-filled pore space increasing 125% compared to 20%

TABLE 1. Effect of Soil Bulk Density and Water-Filled Pore Space on Soil Respiration in a Norfolk Soil During Incubation†.

WFPS‡	Bulk Density (Mg/m^3) 1.4	1.6	1.8	Mean
	(mg CO_2-C/kg soil)			
60	116.7	40.0	40.0	65.6 a
65	65.0	32.3	35.0	44.1 b
70	75.7	28.3	27.3	43.8 b
75	44.7	28.0	27.7	33.4 b
Mean	75.5 a	32.5 b	32.2 b	

† Soil incubated at 25°C for 21 days. Means followed by the same letter are not significantly different at the α = 0.05 level as determined by Fisher's protected LSD.
‡ WFPS = Water-filled pore space.

for 1.4 and 1.8 Mg/m^3 soil bulk density, respectively. No significant interaction between water-filled pore space and soil bulk density was observed for aerobic microbial respiration, native N loss, or fertilizer N loss during incubation.

The most plausible explanation for these results is that soil compaction shifted soil conditions to an anaerobic state, resulting in reduced aerobic microbial activity and increased denitrification. Both decreased aerobic respiration and increased denitrification with increasing water-filled pore space are caused by a reduction in O_2 diffusion through soil (23). Soil compaction likely reduced the proportion of large to small pores (24), resulting in a larger internal surface area of soil covered with water even though the total percentage filled with water was not changed. In addition, the continuity of pores was probably reduced with increasing bulk density (24), which in turn reduced O_2 diffusion through the soil.

TABLE 2. Effect of Soil Bulk Density and Water-Filled Pore Space on Soil Native N Loss from a Norfolk Soil During Incubation†.

WFPS‡	Bulk Density (Mg/m^3) 1.4	1.6	1.8	Mean
	($g N/m^3$ soil)			
60	51.0	229.1	243.7	174.6 a
65	60.4	233.3	283.0	192.2 ab
70	58.5	209.6	282.3	217.8 a
75	114.9	247.0	291.5	183.5 b
Mean	71.2 a	229.7 b	275.1 c	

† Soil incubated at 25°C for 21 days. Means followed by the same letter are not significantly different at the $\alpha = 0.05$ level as determined by Fisher's protected LSD.
‡ WFPS = Water-filled pore space.

These factors would shift more soil microsites where denitrification occurs from an aerobic to an anaerobic state within the same level of water-filled pore space.

No differences were observed among bulk density levels and little or no difference was observed among water-filled pore space levels for fertilizer N loss (Table 3). A nearly constant amount of fertilizer N was lost with all compaction and moisture treatments, with an average 61% fertilizer N recovery. While fractionation of isotopic N during denitrification could be partially responsible for these results, the data do indicate that significant levels of denitrification occurred even at 60% water-filled pore space. These results demonstrate that a number of soil microsites were anaerobic even at 60% water-filled pore space. Since treatment differences observed were manifested in the native soil N fraction, this

TABLE 3. Effect of Soil Bulk Density and Water-Filled Pore Space on Fertilizer N Loss from a Norfolk Soil During Incubation†.

WFPS‡	Bulk Density (Mg/m^3)			
	1.4	1.6	1.8	Mean
	($g N/m^3$ soil)			
60	41.8	46.4	39.7	42.6 a
65	61.8	50.7	63.9	58.8 b
70	42.8	53.9	62.8	53.2 ab
75	63.3	55.1	42.9	53.8 ab
Mean	52.4 a	51.5 a	52.3 a	

† Soil incubated at 25°C for 21 days. Means followed by the same letter are not significantly different at the $\alpha = 0.05$ level as determined by Fisher's protected LSD.
‡ WFPS = Water-filled pore space.

study indicates that it is important to examine both soil N as well as fertilizer N when evaluating effects of soil compaction.

Regression analysis of total soil N loss (native soil N loss + fertilizer N loss) due to water-filled pore space and soil bulk density was made. A significant response to water-filled pore space, soil bulk density, and interaction terms was observed, ($R^2 = 0.86$) (Fig. 1). The relationship demonstrates the importance of soil compaction on soil N losses, and indicates that compaction is important in shifting soil conditions toward an anaerobic state within the same level of water-filled pore space.

CONCLUSIONS

Water-filled pore space is a commonly used parameter, because it allows for comparison of moisture levels across soil types with different water holding

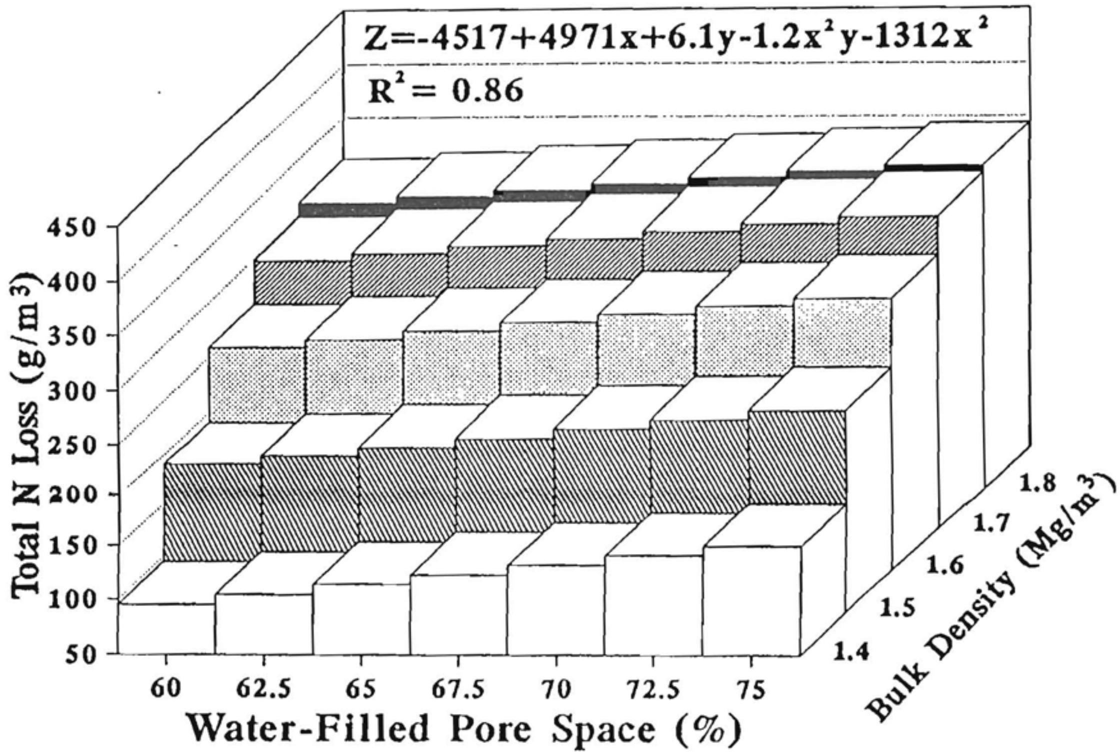

FIGURE 1. Predicted Response of Total N Loss to Soil Bulk Density and Water-Filled Pore Space, where Z = Total N Loss (g/m^3), x = Soil Bulk Density (Mg/m^3), and y = Water-Filled Pore Space (%).

capacities and water movement characteristics (12). Although water-filled pore space is useful as an index of soil microbial activity and soil N loss via denitrification (8), the results from this study indicate that for sandy coastal plain soils, not only the amount of water-filled pores, but also soil bulk density, plays an important role in controlling soil microbial activity. In addition, it is believed that reduced aerobic microbial activity and increased denitrification with increased soil compaction in this study was largely due to alteration of soil pore spaces that promoted soil microsite anaerobiosis.

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